03P10045

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PATENT SPECIFICATION

(11) 1 467 871

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(21) Application No. 25115/74 (22) Filed 6 June 1974

(44) Complete Specification published 23 March 1977

(51) INT. CL.² H02K 19/00

(52) Index at acceptance

H2A 1009 16M 1A 1C7N 201 22 25A 2E11 2E16 2E17 2E4Y 2M 805

(72) Inventors VOLDEMAR VOLDEMAROVICH APSIT
ZIGURD KARLOVICH SIKA
DANIEL PETROVICH KIKUST

(19) THE PATENT OFFICE LONDON

(54) IMPROVEMENTS IN OR RELATING TO SYNCHRONOUS ELECTRICAL MACHINES

(71) We, FIZIKO-ENERGETICHESKY INSTITUT AKADEMII NAUK LATVIISKOI SSR, a Corporation organised and existing under the laws of the Union of Soviet Socialist Republics of ulitsa Aizkraukles, 21, Riga, U.S.S.R., do hereby declare the invention, for which we pray that a patent may be granted us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to brushless synchronous electrical machines.

According to one aspect of the invention, there is provided a brushless synchronous electric machine, comprising a stator carrying an armature winding and a field winding, and a rotor comprising two pole structures having mutually interdigitated poles, the rotor being supported on a shaft for joint rotation therewith relative to the stator, and the armature winding and the field winding being wound from conductors made of superconducting material and being rigidly mounted within a cryostat immovably and coaxially arranged within the rotor.

According to another aspect of the invention, there is provided a synchronous electric machine, comprising a field winding and a three-phase armature winding both wound from conductors made of superconducting material and fixedly mounted on a stator to lie within a cryostat of the machine, and a rotor encompassing the cryostat and comprising two coaxial rotor structures of hollow cylindrical form with interdigitated castellations around their mutually facing ends, the mutual arrangement of the rotor and of the windings being such that the armature winding is positioned in the region of the said interdigitated castellations and the castellations of the rotor structures form magnetic poles of opposite polarity upon d.c. energisation of the field winding.

A brushless synchronous electrical machine embodying the invention will now be particularly described, by way of example, with reference to the accompanying diagrammatic drawings, in which:

Figures 1 and 1′ when superimposed along lines *a-a*, a′-a′, show a longitudinal section of the synchronous machine;

Figure 2 is a section on line II-II of Figure 1; and

Figure 3 is an end view of the machine in the direction indicated by arrow A in Figure 1.

As shown in Figure 1′, the brushless synchronous electric machine comprises a stator 1 having a rotor 2 rigidly secured to a rotatable shaft 3 and coaxially encircling the stator 1.

The stator 1 carries an armature winding 4 disposed on the outer surface of a cylindrically shaped core 5, and a field winding 6 made up of two coils secured by means of bobbins 7 adjacent respective axial ends of the armature winding 4.

The stator 1 is housed in a cryostat 8 which coaxially surrounds it in close-spaced relation. The rotor 2 consists of two claw-shaped pole structures of hollow cylindrical form coaxially arranged with inter-digitated castellations around their facing ends. The rotor structures are bonded together by a filling of a non-magnetic material, such as, for example, aluminium, copper, or plastic. The rotor 2 has its axis vertical and coaxially encircles both the stator 1 and cryostat 8. The cryostat 8 comprises a dual Dewar flask with vacuum heat insulation.

As the cryostat 8 coaxially encloses the machine stator 1 and the rotor 2 coaxially encircles the cryostat 8, the walls of the latter are disposed in the air gap between the stator 1 and rotor 2. For the air gap to be as short as possible, the cryostat walls

are made as thin as possible.

An annular plate 9 is welded to the lower pole structure of the rotor 2.

The plate 9 of the rotor 2 is screwed to the shaft 3 at 10. The shaft 3 is rotatably mounted in bearings 11, the latter being secured in a bearing housing 12. A spacer 13 and a cover 14 serve to locate the bearings 11 in position.

The cylindrical core 5 of the stator 1 is made of an insulating material, for example, glass-fibre-reinforced plastic, or fabricated in the form of a stack of electrically insulated thin ferromagnetic sheets of a metal, such as steel, holmium, or dysprosium.

The cylindrical core 5 of the stator 1 and the bobbins 7 of the field winding 6 are fastened to a tube 15.

The wire of the armature winding 4 and field winding 6 is made of a superconducting material, such as, for example, Nb-Mr, Nb-Ti, Nb_3Ga, the superconducting wire used for the armature winding being made from extremely thin strands of the aforementioned material to minimise losses due to alternating current.

The armature winding 4 is made up of flat coils in a conventional three-phase connection typical of electric machine armature windings, and these coils are attached to the cylindrical surface of the core 5 by means of a band 16 made, for example, of glass tape.

The field winding 6 is made up of two ring coils which are connected in parallel by means of superconducting lead-outs 17 so as to enable a unidirectional magnetizing force to be produced by the coils. The lead-out 17 of the lower field winding coil (as viewed in Figure 1) passes through an opening 18 in the core 5 and an opening 19 in the upper bobbin 7. These openings also serve to improve the cooling of the stator 1.

Thus, the winding 6 has two lead-outs 17, each of which is connected to a respective copper tube 20 which passes through a cover 21 of the cryostat 8 and is appropriately insulated therefrom.

The three-phase armature winding 4 has three superconducting lead-outs 22. The lead-outs 22 pass through further openings 19 of the upper bobbin 7 and are connected to copper tubes (not shown) which pass through the cover 21 of the cryostat 8 and are insulated therefrom.

The cryostat 8 is intended to cool the stator 1 to the temperature of liquid helium, i.e. to 4.2°K. The cryostat 8 comprises an inner container and an outer container which are vacuum-insulated from each other and are also separated by an intermediate heat shield of liquid nitrogen.

The inner container of the cryostat 8 comprises a cylinder 24 (Figures 1 and 1), a hemispherical bottom 25 and a flange 26. During operation of the electric machine, the cylinder 24 and bottom 25 are permeated by an alternating magnetic flux, and therefore, to ensure against possible eddy-current heating of the cylinder 24 and bottom 25, these elements are made from glass-fibre-reinforced plastics.

The outer container of the cryostat 8 comprises two cylinders 27 and 28 of different diameters, a flat bottom 29, an intermediate ring plate 30 and a flange 31.

The cylinder 27 is made from glass-fibre-reinforced plastics. The other components of the outer cryostat container may be fabricated from any suitable constructional material, such as, for example, stainless steel or glass-fibre-reinforced plastics.

The intermediate ring plate 30 is welded to a housing 32 which terminates in a flange supporting the bearing housing 12 fastened thereto by means of bolts 33.

The bottom 29 of the outer container of the cryostat 8 rests on a stationary support 34 located by a bearing 35 in the end face of the shaft 3, inner and outer races of the bearing 35 being respectively fast with the support 34 and the shaft 3. The inner and outer cryostat containers are bolted together at 36.

The flange 31 has an annular groove with a vacuum rubber washer 37 inserted therein which seals the joint between the inner and outer cryostat containers. The chamber formed between the walls of the inner and outer cryostat containers accommodates a cylindrically shaped copper shield 38 surrounding the inner container of the cryostat 8. A partition 39 is arranged between the copper shield 38 and the flange 26 of the inner cryostat container. The partition 39 is fabricated from stainless steel in the form of a cylinder. The partition 39, the shield 38 and the cylinder 24 define an annular space 40, filled with liquid nitrogen through a port 41; the remaining space 42 between the inner and outer cryostat containers is evacuated.

Liquid nitrogen in the space 40 serves as a heat screen against an inflow of external heat to the inner container through the side walls of the cryostat 8, which would otherwise occur as a result of heat transfer through the heat conducting walls of the inner container. The inner container of the cryostat 8 is filled with liquid helium to completely immerse the machine stator 1 in liquid helium.

The armature winding 4 and field winding 6 fitted on the stator 1 are exposed to liquid helium flowing around them and are cooled thereby to the boiling point of liquid helium at normal pressure, i.e. to 4.2°K. The openings 18 in the core 5 and

openings 19 in the bobbins 7 serve to improve the convection of liquid helium for proper cooling of the core 5, armature winding 4 and field winding 6. The inner cryostat container is so arranged internally of the outer container that their walls do not touch.

To ensure good heat insulation, the space 42 between the walls of these containers is highly evacuated.

To improve the vacuum in the space 42, use is made of activated birch charcoal 43 functioning as an adsorption medium. This activated charcoal is placed on a ring shelf 44 soldered to the copper shield 38, and is covered over by a copper mesh. The presence of charcoal permits the evacuation of the inner space 42 down to a pressure of 10^{-1} to 10^{-2} mm Hg. On filling the annular space 40 with liquid nitrogen, the vacuum in the space 42 reaches 10^{-6} to 10^{-8} mm Hg. Liquid nitrogen prevents influx of heat into the cooled zone of the machine, i.e. serves as an outer heat barrier.

Coating the outer surface of the inner container of the cryostat 8 with silver or aluminium additionally decreases heat influx due to thermal radiation into the cooled zone of the machine.

To minimize heat influx due to heat transfer through the walls of the cryostat 8, it is advisable that the walls of the inner container, central tube 15 and partition 39 should be as thin as possible with regard to the mechanical strength of the selected material, and the cryostat 8 should be made long.

The top of the inner container of the cryostat 8 is closed by the cover 21. A bushing 46 is welded to the central portion of the cover 21 and a thin-walled tube 51 of stainless steel extends through this bushing and is sealed in its passage therethrough by a gasket 47 made from vacuum rubber, a thrust ring 48 and a nut 49 threadedly-engaging the bushing 46. As the nut 49 is tightened, the gasket 47 is compressed and fixes the tube 51. An internally-threaded housing 50 is soldered to the upper ends of the tube 51 and of the central tube 15. The tube 51 reduces the heat influx from the cover 21 of cryostat 8 to the central tube 15. In the foregoing manner, the core 5, the stator 1 and the field winding coils are accurately and adjustably mounted relative to the claw-shaped pole structures of the rotor 2. A gasket 52, a ring 53 and an externally-threaded nut 54 are accommodated in the housing 50 and ensure tight sealing of a helium supply pipe 55 through which liquid helium is introduced into the cryostat 8 from a tank or a liquefier.

Evaporated gaseous helium is removed through an outlet pipe 56 forming part of a twin pipe arrangement for minimizing heat influx. The twin pipe arrangement is connected to the cryostat by means of a fastening assembly consisting of a housing 57, a gasket 58, a thrust ring 59 and a nut 60. To minimize heat influx, the housing 57 is connected to the cover 21 of the cryostat 8 through a thin-walled tube 61 of stainless steel.

Five identical fastening assemblies for the copper tubes 20 connected to the lead-outs of the machine windings (three lead-outs of the armature winding 4 and two lead-outs of the field winding 6 are symmetrically arranged together with the outlet pipe 56 around the bushing 46 on the cover 21 (Figure 3). The fastening assembly for the copper tube 20 connected to a lead-out of the field winding 6 is shown in longitudinal section in Figure 1. To reduce heat influx, a housing 62 of this fastening assembly is attached to the cover 21 of the cryostat 8 through a thin-walled tube 63 of stainless steel. The housing 62 accommodates a washer 64, a gasket 65 of vacuum rubber, a tube 66 with a shoulder and a nut 67. The washer 64 and tube 66 are made from an insulating material. The tube 66 is fitted over the copper tube 20 and insulates the latter from the nut 67. The bottom end of the nut 67 bears against the shoulder of the tube 66. As the nut 67 is tightened, the shoulder of the tube 66 compresses the rubber gasket 65 and fixes the copper tube 20 in position.

With the machine operating, the helium in the inner container of the cryostat 8 is maintained at a level which is 20 to 30 mm above the upper coil of the field winding 6 and the level of liquid nitrogen in the annular space 40 is kept at 40 to 55 mm above the point of attachment of the copper shield 38 to the inner container of crystal 8. In addition to the liquid nitrogen port 41, a nitrogen vapour outlet port (not shown) in communication with the space 40 is also provided.

During continuous operation of the machine, it is advisable to include the inner container of the cryostat 8 in a closed loop with a helium liquifier by directly connecting the liquid helium outlet pipe 56 and the supply pipe 55 to the helium liquifier.

The field winding 6 when energized with direct current develops an axial magnetizing force that produces an axial magnetic flux in the central portion of the stator 1. The flux closes through the pole structures around the stator 1 partially permeating the armature winding 4; this portion of the flux is useful, and that portion of the flux which closes directly between the opposite-polarity pole structures by-passing the armature winding 4 is stray flux. The path of

the useful flux is indicated in Figure 1 by dashed line 68.

An increase in the useful flux is desirable since it enables a desired output voltage to be obtained with a reduced number of turns of the armature winding 4 and, therefore, enables the weight and size of the machine to be diminished. To increase the useful flux, its permeance, compared to that of the stray flux, should also be increased. For this purpose, the core 5 of stator 1 should preferably be made from ferro-magnetic material. Furthermore, in order to reduce heating due to eddy currents in the core 5, it should be fabricated in the form of a stack of thin electrically insulated sheets. Since the core 5 is completely submerged in liquid helium and its temperature is close to 4.2°K, it is expedient to use rare-earth metals for its fabrication, such as dysprosium or holmium which at the temperature of liquid helium become good ferro-magnets with higher magnetic permeabilities than that of steel. Dysprosium and holmium, as is known, become magnetically saturated in the neighbourhood of 4 teslas. By fabricating the core 5 as a stack of thin sheets made from the above-mentioned metals, it is possible to achieve a field strength in the gap between the stator 1 and rotor 2 in the order of 2 teslas.

To increase still further the useful flux, a minimum length gap should be provided between the stator 1 and rotor 2. For this reason, the liquid nitrogen heat screen is not interposed between the inner and outer cryostat container walls passing through this gap. The required heat insulation of this portion of the cryostat is effected solely by high vacuum in the space 42 between the inner and outer containers of the cryostat 8, the annular space 40 filled with liquid nitrogen providing heat screening only in the upper portion of the cryostat 8.

The described machine can be operated as an alternator by d.c. energising the field winding 6 and rotating the rotor 2 to cause an alternating polarity field to progress circumferentially around the armature winding 4. The machine can also be used as a synchronous motor by setting up a rotating magnetic field by 3-phase energisation of the armature winding 4, and simultaneously supplying direct current to the field winding 6.

The hereinbefore described synchronous machine is efficient, simple and reliable. Due to the use of a superconducting field winding, the magnetising force set up by the field winding can be made sufficiently great as to enable the ferro-magnetic magnetic circuit of the machine to be minimised, preserving only the claw-shaped pole structures made of steel and, in some cases, a stator core made in the form of a steel cylinder.

As compared to a non-superconducting machine, the weight and size of the described machine are considerably reduced and its efficiency increased (due to a decreased Joule resistive heating in the field winding 6 and armature winding 4, and also due to decreased losses in the magnetic-circuit steel).

By rigidly mounting the field winding 6 and armature winding 4 in the cryostat 8 and arranging the steel, windingless, rotor 2 outside the cryostat 8, a major source of external heat influx is eliminated, i.e. the massive shaft penetrating inside the cryostat. Furthermore, a major internal heat source is also eliminated, namely, turbulence and drag in the refrigerant due to rotor rotation. It should be noted that since a helium liquefier consumes approximately one kilowatt of electrical energy to remove one watt of heat from inside the cryostat elimination of heat release sources inside the cryostat enables the overall efficiency of machine and liquefier to be significantly increased.

A further source of heat inside the cryostat due to eddy currents in the cryostat walls is also eliminated due to the fact that the walls of the cryostat 8 are made from a dielectric material. Another advantage of the described arrangement is that the amount of liquid helium required for cooling the superconducting windings is reduced.

The cryostat 8 is of a simple design having no rotating parts and, therefore, no complicated sealing devices.

The reliability of the machine is enhanced as compared to synchronous machines employing brush gear due to the absence of slide contacts in the electric circuitry of the machine.

The described synchronous machine can be used as a generator at high-power plants for both land based installations (electric power stations) and mobile installations (large sea-going vessels, air and spacecraft).

WHAT WE CLAIM IS:—

1. A brushless synchronous electric machine, comprising a stator carrying an armature winding and a field winding, and a rotor comprising two pole structures having mutually interdigitated poles, the rotor being supported on a shaft for joint rotation therewith relative to the stator, and the armature winding and the field winding being wound from conductors made of superconducting material and being rigidly mounted within a cryostat immovably and coaxially arranged within the rotor.

2. A machine according to claim 1, comprising an elongate housing surround-

ing the cryostat and the rotor, one end portion of the housing being rigidly secured to the cryostat and the opposite housing end portion having an opening through which a shaft of the rotor extends, the cryostat being supported adjacent said opposite housing end portion in a bearing having an inner race fixed to the cryostat and an outer race fixed to an end face of the rotor shaft.

3. A machine according to claim 1 or claim 2, in which the cryostat comprises inner and outer containers separated by an evacuated space, at least those portions of the container which lie within the rotor-stator gap of the machine being made from an insulating material.

4. A machine according to any one of the preceding claims, in which the armature winding is made up of separate coils electrically connected to one another and arranged on the outer surface of a cylindrical core attached to a tube arranged within the cryostat and fixed to a cover of the cryostat.

5. A machine according to claim 4, in which the core of the armature winding is made from a material which possesses ferromagnetic properties at the temperature of liquid helium, the core being in the form of a stack of thin sheets of said material electrically insulated from one another.

6. A machine according to claim 4 or claim 5, in which the field winding comprises two ring coils arranged at respective ends of the armature winding on said tube.

7. A synchronous electric machine, comprising a field winding and a three-phase armature winding both wound from conductors made of superconducting material and fixedly mounted on a stator to lie within a cryostat of the machine, and a rotor encompassing the cryostat and comprising two coaxial rotor structures of hollow cylindrical form with interdigitated castellations around their mutually facing ends, the mutual arrangement of the rotor and of the winding being such that the armature winding is positioned in the region of the said interdigitated castellations and the castellations of the rotor structures form magnetic poles of opposite polarity upon d.c. energisation of the field winding.

8. A brushless synchronous electric machine, substantially as hereinbefore described with reference to the accompanying drawings.

MATHISEN, MACARA & CO.,
Chartered Patent Agents,
Lyon House,
Lyon Road,
Harrow,
Middlesex, HA1 2ET.
Agents for the Applicants.

Printed for Her Majesty's Stationery Office by The Tweeddale Press Ltd., Berwick-upon-Tweed, 1977. Published at the Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

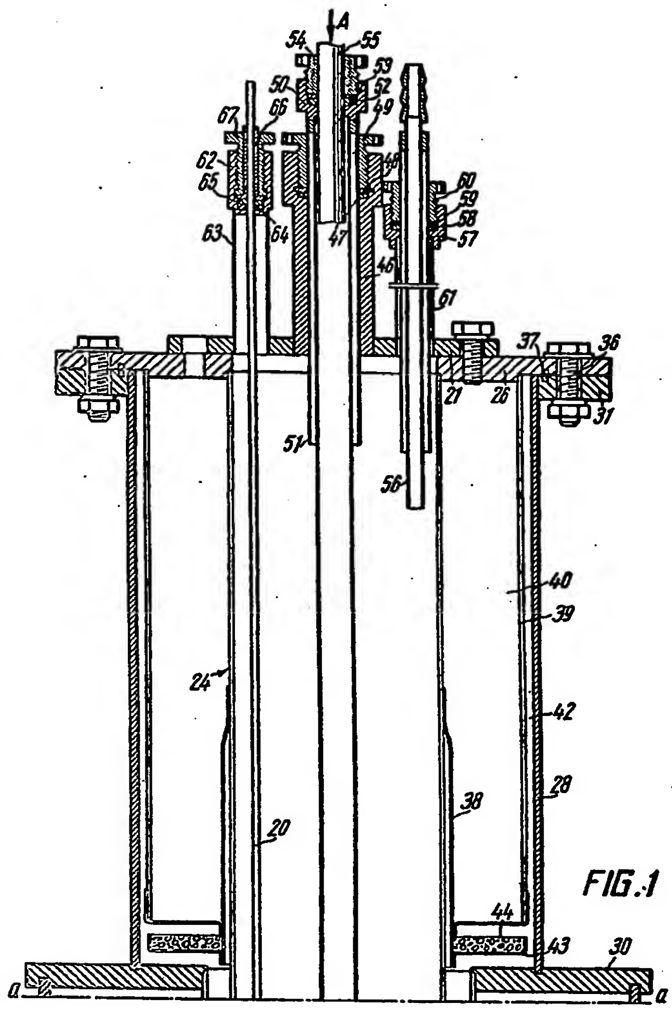
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FIG. 1

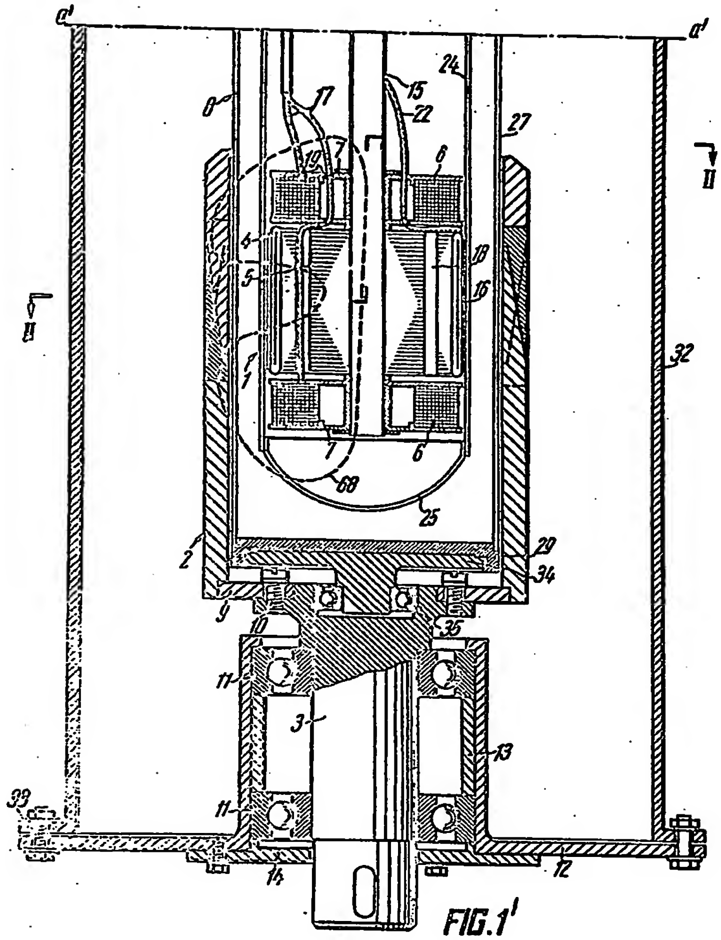
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FIG. 1'

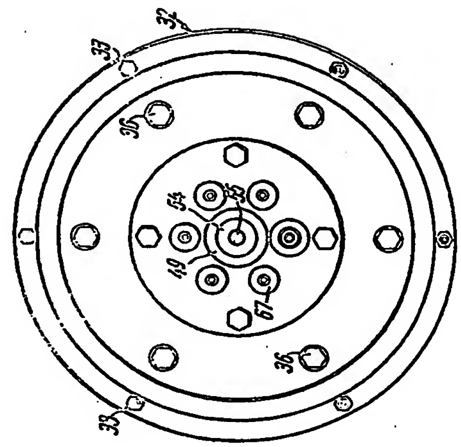

FIG.3

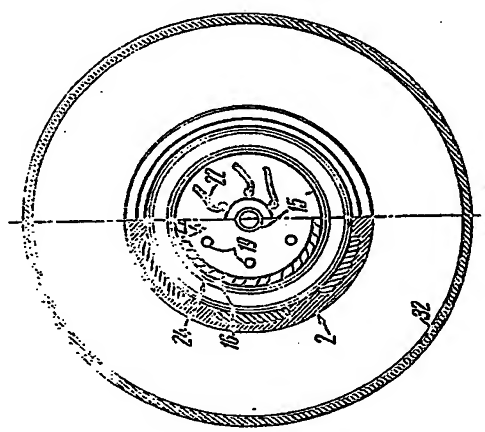

FIG.2